Journal of Cleaner Production 201 (2018) 1081–1091

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A goal programming model for sustainable reverse logistics operations planning and an application

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A R T I C L E I N F O

Article history:
Received 2 January 2018
Received in revised form
15 July 2018
Accepted 10 August 2018
Available online 13 August 2018

A B S T R A C T

Global concerns about climate change and its environmental consequences, social factors and economic constraints require pursuit of a new approach to the supply chain planning at the strategic, tactical and operational levels. Recovery of waste electric and electronic equipment (WEEE) has become an important issue in the developing economies, as legislations that mandate manufacturers and importers to take back the wastes of their electrical and electronic products (WEEE) has been promulgated. Therefore, this study addresses the process of collecting WEEE products from service points, transporting them to recycling facilities, and recovery of the waste materials. Our framework considers triple-bottom-line approach and employs goal programming to reach economic, social and environmental targets. A multi-facility, multi-product and multi-period mathematical model is proposed, considering the real conditions, for the first time in the literature. In addition, this goal programming approach is illustrated on a WEEE reverse supply chain of the household appliances.

1. Introduction

Global concerns about climate change and its environmental consequences, social factors and economic constraints require pursuit of a new approach to the supply chain planning at the strategic, tactical and operational levels. In this day and age, it is not enough to think only from economic perspective. Especially private companies aim cost minimization, but it is also necessary for them to consider the environmental protection and the social impact. At this point, governments consider to amplify social benefit and make legislations to reduce unfavorable environmental impact.

Sustainability is either used to sustain an implementation or to emphasize environmental awareness both in academic and non-academic resources. Although both definitions are correct, they are incomplete. The approach used in analyzing sustainability is described as triple bottom line (TBL) accounting. The TBL concept states that for a system to be sustainable, economic, environmental and social requirements must be reached at a minimum (Jeurissen, 2000). As Linton et al. (2007) expressed, to achieve a sustainable supply chain, each fragment of it should have environmentally friendly procedures including product design, manufacturing, usage, recycling, and transporting among suppliers, manufacturers, and customers.

Recovery of WEEE products has become an important issue in the developing economies. However, companies are reluctant or not capable of entering this market. Manufacturers, on the other hand, are under pressured according to the market trend and obliged to implement environmental regulations (Kumar and Putnam, 2008). A regulatory control of waste electric and electronic equipment that mandates manufacturers and importers to take back their products has been promulgated (Ministry of Environment and Urbanization, 2012).

Based on the aforementioned considerations, this paper addresses the issue of the collecting waste products from service points and transporting them to recycling facilities. Our framework considers triple-bottom-line approach and employs goal programming to reach economic, social and environmental targets. A goal-programming model has been developed in tactical operations planning of the reverse supply chains with multi-facility, multi-product and multi-period. The proposed mathematical model can be used for transportation and recovery operations decision making with a TBL perspective and it can be extended to different types of reverse supply chains. In addition, we illustrate our approach on a WEEE reverse supply chain of the household

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https://doi.org/10.1016/j.jclepro.2018.08.104
0959-6526/

appliances.

The paper is structured as follows. Section 2 offers a sustainability based literature review to assess the optimization papers in forward/reverse logistics network design. To further explain the TBL accounting, the proposed framework is illustrated and economic, environmental and social perspectives are discussed in section 3. To design reverse logistics network, a goal-programming model is developed in section 4. Section 5 explains Augmented ε-constraint methodology and section 6 presents the Case Study. Later, results and discussion on the case study are presented. Lastly, conclusion of the paper and further research are explained in section 8.

2. Literature review

A significant amount of sustainable supply chain research has been conducted considering various sustainability indicators related to TBL for managerial decision making in supply chain management (SCM) (Carter and Rogers, 2008) and operations management (Drake and Spinler, 2013; Kleindorfer et al., 2005), in particular. Compared to the extensive research on environmental aspects and especially economic issues, the social aspects are neglected in the sustainable SCM literature. Yura (1994) elaborated social issues, Brent et al. (2007) and Abreu and Camarinha-Matos (2008) studied on socio-economic issues and Clift (2003) detailed socio-environmental interfaces. Paksoy et al. (2010) proposed a closed loop supply chain design using multi-objective mixed-integer linear programming. The model minimizes cost and greenhouse gas emissions at the same time. Tseng and Hung (2014) considered both social costs caused by the carbon dioxide emissions and operational cost in an apparel manufacturing supply chain network. Transportation planning in reverse and closed-loop supply chain design is also discussed at the tactical level, and mathematical models are proposed (Dekker et al., 2013).

A large number of multi-facility multi-product deterministic facility location problems were studied in the literature. However, operational planning has attracted little attention. Also, sustainability approach requires multiple objectives to be achieved. Gonela et al. (2015) proposed a stochastic mixed integer linear programming model for bioethanol supply chain and evaluated the results under different sustainability concerns. Krumwiede and Sheu (2002) developed a reverse logistics decision-making model for third-party logistics providers to help engage in the reverse logistics business. Hung Lau and Wang (2009) investigated the feasibility of current reverse logistics theories and models for electronics industry taking into account developing countries like China. A mixed integer programming model is proposed by Shih (2001) for reverse logistics network design considering cost parameters including sale revenue of reclaimed materials. Kara et al. (2007) calculated collection cost of waste appliances in reverse logistics network using discrete event simulation. Mutha and Pokharel (2009) designed a multi-echelon network including a consolidation warehouse into the system before they are sent to the reprocessing center for inspection or dismantling. Tuzkaya et al. (2011) proposed a two staged multi objective model for reverse the logistics network design problem and presented its application in the Turkish white appliances industry.

Bal and Satoglu (2017) used sustainability perspective as well as legal requirements to set up a goal-programming model to optimize a global white appliance manufacturers' reverse logistics system. Coskun et al. (2016) proposed a goal-programming model to re-design green supply chain network considering three different customer segments. The results demonstrated that the increase in the number of green consumers expanded the tendency of the retailers to cooperate with the suppliers to redesign the supply chain, to fit the consumers' expected greenness level. A

Table 1

Reviewed Articles about sustainable supply chain design. (Notation – BD: benders decomposition, E: economic, En: environmental, FMoO: fuzzy multi objective optimization GP: goal programming, MILP: mixed integer linear programming, MINLP: mixed integer non-linear programming, MoSO: multi objective stochastic optimization, RO: Robust optimization, S: social, SMILP: stochastic mixed integer linear programming SO: stochastic optimization).

	Network structure	Objective	Modelling approach	Case study
Anvari and Turkay, 2017	Forward	EEnS	MILP	Yes
Arampantzi and Minis, 2017	Forward	EEnS	GP	Yes
Feitó-Cespón et al., 2017	Reverse	EEnS	MoSO	Yes
Safaei et al., 2017	Closed-loop	E	MILP	Yes
Sarkar et al., 2017	Closed-loop	EEn	MINLP	No
Yu and Solvang, 2017	Reverse	EEn	MoSO	No
Demirel et al., 2016	Reverse	E	MILP	Yes
Govindan et al., 2016a	Closed-loop	EEnS	MILP	Yes
Govindan et al., 2016b	Reverse	EEnS	FMoO	Yes
Shaw et al., 2016	Closed-loop	En	BD	No
Ene and Oztürk, 2015	Reverse	E	MILP	No
Zhou and Zhou, 2015	Reverse	E	MINLP	Yes
Hashemi et al., 2014	Closed-loop	E	MILP	No
Ozceylan et al., 2014	Closed-loop	E	MINLP	No
Roghanian and Pazhoheshfar, 2014	Reverse	E	MILP	No
Soleimani and Govindan, 2014	Reverse	E	SO	No
Amin and Zhang, 2013	Closed-loop	EEn	MoSO	No
Diabat et al., 2013	Closed-loop	EEn	MILP	No
Ozceylan and Paksoy, 2013	Closed-loop	E	MILP	No
Ramezani et al., 2013	Closed-loop	E	MoSO	No
Alumur et al., 2012	Reverse	E	MILP	Yes
Das and Chowdhury, 2012	Reverse	E	MILP	No
Kannan et al., 2012	Reverse	En	MILP	Yes
Ozkır and Başligıl, 2012	Closed-loop	E	MILP	No
Fonseca et al., 2010	Reverse	ES	MoSO	Yes
Ramudhin et al., 2010	Forward	EEn	GP	No
Lee and Dong, 2009	Reverse	E	SMILP	No
Aras and Aksen, 2008	Reverse	E	MINLP	No
Demirel and Gokçen, 2008	Closed-loop	E	MILP	No
Pati et al., 2008	Reverse	EEn	GP	Yes

similar research was carried out by Ghosh and Shah (2015). They verified that supply chain stakeholders are provided better opportunities to launch green initiatives by green consumer markets.

In Table 1, the papers are summarized concerning economic (E), environmental (En) and social (S) objectives. Economic objectives are considered at all of the papers. Sixteen papers used only economic objectives. Both economic and environmental objectives are used by Sarkar et al. (2017), Yu and Solvang (2017), Pati et al. (2008), Amin and Zhang (2013), Diabat et al. (2013), Ramudhin et al. (2010). However, these studies but do not have any social objective. Especially recently published papers are using social objectives in addition to economic and environmental objectives (Anvari and Turkay (2017), Arampantzi and Minis (2017), Feitó-Cespón et al. (2017), Govindan et al. (2016a), Govindan et al. (2016b)). In spite of many papers with economic objectives, sustainability approach is not widely studied in the literature. Multi-objective optimization has been used increasingly in recent years.

In addition, there are only a few papers using goal programming (Arampantzi and Minis (2017), Ramudhin et al. (2010), Pati et al. (2008)), in the literature. Arampantzi and Minis (2017) considered only forward logistics network design, especially facility location problem and capacity extension decisions. Anvari and Turkay (2017) also studied the facility location problem that incorporates the TBL approach for sustainability.

Colapinto et al. (2015) presented a comprehensive review of the GP studies. This technique has been frequently used for solving multi-criteria decision problems concerned with engineering design, management and social sciences. Design of the hybrid manufacturing systems (Satoglu and Suresh, 2009), paper recycling system (Pati et al., 2008), closed-loop battery supply chains (Subulan et al., 2015a), tire closed-loop supply chains (Subulan et al., 2015b) were performed by means of GP or fuzzy GP.

To the best of authors' knowledge, this is the first study in the literature that proposes a goal programing model for reverse supply chains based on a TBL approach and performs a case study in household goods (WEEE) recovery industry. Our detailed literature review supports this finding.

3. Proposed framework for operations planning

In this section, we present the proposed decision making framework (see Fig. 1). This decision-making framework can be

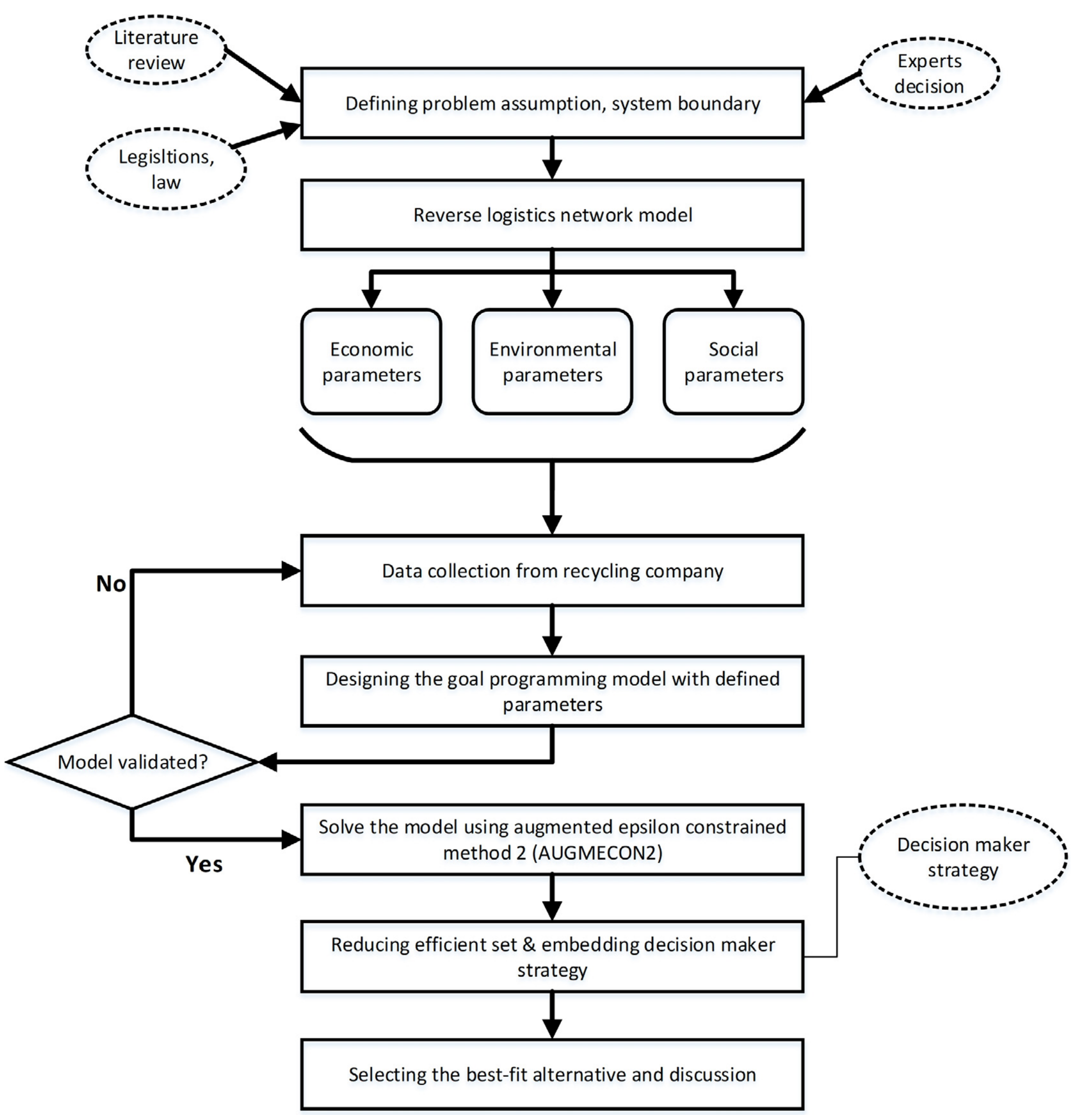

Fig. 1. Schematically representation of the decision framework.

applied for operations planning in any sustainable supply chain. In our case, operations planning problem requires definition of the system boundary and determination of the model assumptions utilizing the knowledge in the related literature and experts working on reverse supply chain networks. In our network we consider customers, WEEE collection sites, recycling facilities, raw material markets, and government. The framework of the model is completed by considering economic, environmental and social factors. Since we optimize conflicting objectives in the Pareto optimal set we need to implement a decision maker strategy where experts are involved.

One of the challenging sides of analyzing sustainability is the conflict between essential factors. It is absolutely necessary for companies to maintain their profitability so that they can sustain their existence, but also the responsibility for nature and society must not be ignored. Some guidance (e.g. ISO 14001) and regulations exist regarding environmental responsibility which force the companies. As for the performance of the supply chain, not only economic and environmental aspects but also social factors are important (Ramudhin et al., 2010). Nevertheless, social perspective remains an area that received less attention (Seuring and Müller, 2008).

Economic parameters: The most important thing for investors is the profit of the investment. We did the primary considerations for parameters selection in the economic dimension in this context. We focused on the cost of running reverse logistics operations, but not the initial investment cost. The cost items include the fixed cost of recycling the products, labor cost, transportation cost and penalty cost of uncollected products. Besides, revenue item is considered as the monetary value of the recycled materials such as aluminum, copper etc. (Shih, 2001).

Environmental parameters: We derived emission and waste rates used in the model from recognized data sources including web sites (www.myclimate.org, footprint.wwf.org.uk, www.nature.org), research articles (Eskandarpour et al., 2015; Neumüller et al., 2015) and reports (Trends in Global CO_2 emissions: 2016, Inventory of US greenhouse gas emissions and sinks: 1990–2015). In addition, we considered performance characteristics of the trucks from manufacturers such as Volvo (Martersson, 2010). Based on (Martersson, 2010), we have calculated the emission of carbon dioxide for a 40-ton truck for which the payload is 27 tons and the fuel consumption is 0.35 L per kilometer, as follows:

0.35 l/km $\times$ 2.7 kg/l per 27 tons $\approx$ 0.035 kg/ton-km.

The proposed model considers not only emission from transportation but also facility operations. Because a facility creates emission from power consumption, employee transportation, paper consumption and use of computers as well.

In Table 2, we show compared data of Euro6 and Euro 5 emission standards for the heavy duty engines (Williams and Minjares, 2016).

Social parameters: International Guidance Standard on Social Responsibility-ISO 26000 (ISO, 2010) is a good reference for social criteria identification. ISO 26000 sets the frameworks of social responsibility in seven major topics: organizational governance, human rights, labor practices, the environment, fair operating practices, consumer issues, community involvement and development. Also, Anvari and Turkay (2017) divides social factors into five categories: demand satisfaction, resource equity, job opportunity, regional development, security level at the location, medical facility access level. These factors are used for selection of a facility location. However, it can also be considered as the local development goal, and we determined keeping the number of workers at a certain level for an operating facility as a social goal. The main reason behind this is the variability in the demand of WEEE to be recycled (Bal et al., 2018) which can cause layoffs at some period. For both employers and governments, it is important to keep workforce level at a certain level. Governments do not wish the workforce level to decrease. On the other hand, employers often do not wish to pay compensation by layoffs and confront with unions. Thus, we aimed to provide more regular work opportunity to employees.

Table 2
Euro 5 and Euro 6 standards for heavy-duty diesel engines: steady state testing (Notation – CO: carbon monoxide, ELR: European load response, ESC: European stationary cycle, HC: hydrocarbon, NOx: nitrogen oxide, PM: particulate matter, PN: particle number, WHSC: world harmonized stationary testing).

	Test	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)	PN (1/kWh)
Euro VI	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}
Euro V	ESC&ELR	1.5	0.46	2.0	0.02	

PM = 0.13 g/kWh for engines < 0.75 dm3 swept volume per cylinder and a rated power speed > 3000 min^{-1}.

4. Proposed goal programming model

In this paper, we address the operations planning problem for a reverse supply chain considering four goals. The proposed model determines the timing and amount of WEEE collection from the pre-determined points considering cost & revenue items, emission, available workforce, collection target, capacity of the recycling facility and distance. There are four goals determined according to the cost minimization, environmental effect reduction, workforce balance and catching legal targets. The model handles operations planning problem, which has a TBL accounting perspective within a multi-product, multi-facility and multi-period case.

Model Assumptions.

- Products are collected from the central point of the city. Inner-city routing is out of the scope of this study.
- Cost of recycling does not change with years.
- The numbers of collection sites are known and locations of the recycling facilities are predetermined.
- The specific facility that can recover a product type is predetermined.
- Cost parameters are foreknown as material, operation, recycling, transportation, hiring, laying off and fixed cost.
- The holding cost, stock out cost and storage cost are disregarded.

Model notation.

Sets:

i: set of all types of products, $i \in 1 \ldots I$
j: set of all types of raw recycled materials, $j \in 1, \ldots J$
k: set of all cities, $k \in 1 \ldots K$
l: set of all facilities, $l \in 1 \ldots L$
t: set of all periods, $t \in 1 \ldots T$
p: set of periods, $p \in 1 \ldots T$

Scalars:

BG : *big number*
EOQ : *economic order quantity for a city (A full – truck load)*
$FTL(vehicle)$: *full truck load per transport vehicle*
$G(gram/unit\ vehicle/Km)$: *amount of emission per unit transport per km*
$MR(\%)$: *minimum collection rate*
$RB(\$/person)$: *employment cost of a worker*
$RC(\$/person)$: *hiring cost of a worker in \$*
$RD(\$/person)$: *layoff cost of a worker in \$*
$RT(\$/vehicle)$: *fixed cost of transportation in \$*
$WM(\%)$: *maximum workforce level*; $(WM \geq 100\%)$

MH (Hour): Number of work hours per month per one worker.

Parameters:

$ß_t(gram)$: *target value of* CO_2 *emission due to all transportation process*
$CAP_{lt}(unit\ product)$: *capacity of facility l in period t*
$d_{kl}(km)$: *distance between demand location k and recycling facility location l*
$DM_{ikt}(unit)$: *amount of product i sold in region k at period t*
$E_i(gram)$: *amount of emission stem from recycling of a product i*
$\varepsilon_t(gram)$: *target value of* CO_2 *emission due to all recycling processes at period t*
$FA_i(hour)$: *required person – hour workforce to recycle product i*
$F_t(unit)$: *collection target at period t*
$L_t(person)$: *target number of worker in period t*
$MS_{ij}(\$/kg\ mterial)$: *monetary value of material j recycled from product i*
$O_{it}(\%)$: *the percentage at which product i should be collected accordin to the legislation*
$PR_i(\$/vehicle/Km)$: *cost of transportation of product i*
$RA_i(\$/unit\ product)$: *recycling operation cost of product i*
$RP_i(\$/unit\ product)$: *penalty cost of uncollected product i*
$RS_{ij}(kg/unit\ product)$: *amount of material j recycled from product i*
$SM_{it}(unit\ product)$: *amount of product i sold in period t*
$TR_{it}(\$)$: *target total cost of recycling of product i in period t*
$Employment\_target_{lt}$: *Number of people targeted to be employed at facility – l, in period – t.*

Decision variables:

H_{lt} : *number of workers hired at facility l during period t*
M_{lt} : *number of redundant workers at facility l during period t*
W_{lt} : *number of workers employed at facility l in period t*
X_{ikt} : *collected – recycled number of product i in period t from region k*

$$Y_{kt}\begin{cases}1, & \text{if product } i \text{ is collected in period } t \text{ from region } k\\ 0, & \text{otherwise}\end{cases}$$

$f_{it}^+, f_{it}^-, tr_{it}^+, tr_{it}^-, e_t^-, e_t^+, p_{lt}^+, p_{lt}^-$: *Deviational variables.*

Objectives:

$$Min\ Z1 = \sum_t \sum_i f_{it}^- \tag{1}$$

$$Min\ Z2 = \sum_t \sum_i tr_{it}^+ \tag{2}$$

$$Min\ Z3 = \sum_l \sum_t p_{lt}^- \tag{3}$$

$$Min\ Z4 = \sum_t e_t^+ \tag{4}$$

Subject to :

$$\sum_i \sum_k \sum_l X_{ikt} RA_i + W_{lt} RB + H_{lt} RC + M_{lt} RD + \sum_i \sum_k \sum_l d_{kl} PR_i \frac{x_{ikt}}{FTL} + \sum_i \sum_k \frac{x_{ikt}}{FTL} RT + \sum_i \sum_k (DM_{ikt} - X_{ikt}) RP_i - \sum_i \sum_j \sum_k X_{ikt} RS_{ij} MS_{ij} = \sum_i \left(TR_{it} + tr_{it}^+ - tr_{it}^-\right); \quad (\forall t \in T) \tag{5}$$

$$\sum_k \sum_t X_{ikt} = \sum_t O_{it} SM_{it} + f_{it}^+ - f_{it}^-; \quad (\forall i \in I) \tag{6}$$

$$\sum_i \sum_k X_{ikt} E_i + \sum_k \sum_l \frac{X_{ikt}}{FTL} Gd_{kl} = \varepsilon_t + \beta_t + e_t^+ - e_t^-; \quad (\forall t \in T) \tag{7}$$

$$W_{lt} = Employment\_target_{lt} + p_{lt}^+ - p_{lt}^-; \quad (\forall t \in T, \forall l \in L) \tag{8}$$

$$W_{lt} \geq \sum_i X_{ikt} FA_i / MH; \quad (\forall t \in T, \forall l \in L) \tag{9}$$

$$W_{lt} \leq \sum_i X_{ikt} FA_i \times WM / MH; \quad (\forall t \in T, \forall l \in L) \tag{10}$$

$$W_{lt-1} + H_{lt} - M_{lt} = W_{lt}; \quad (\forall t \in T, \forall l \in L) \tag{11}$$

$$\sum_i \sum_k X_{ikt} \leq CAP_{lt}; \quad (\forall t \in T, \forall l \in L) \tag{12}$$

$$EOQ - \sum_i X_{ikt} \leq BG(1 - Y_{kt}) \quad ; (\forall t \in T, \forall k \in K) \tag{13}$$

$$\sum_i X_{ikt} \leq BG \bullet Y_{kt}; \quad (\forall t \in T, \forall k \in K) \tag{14}$$

$$\sum_i X_{ikt} \geq MR \times \sum_i DM_{ikt}; \quad (\forall t \in T, \forall k \in K) \tag{15}$$

$$\sum_{t=1}^{p} X_{ikt} \leq \sum_{t=1}^{p} DM_{ikt}; \quad (\forall p = 1, \ldots, 12)(\forall i \in I, \forall k \in K) \tag{16}$$

$$All\ variables \geq 0 \tag{17}$$

$$X_{ikt}, H_{lt}, M_{lt}, W_{lt} \in Z^+ \quad (\forall i, k, l, t); Y_{kt} \in \{0, 1\} \tag{18}$$

Objective functions (1), (2), (3), (4) minimizes the negative deviation from WEEE collection target, minimizes positive deviation from cost target, negative deviation from employment target and positive deviation from total emission target that stems from both transportation and recycling operations. Constraint (5) defines cost that the manufacturer must pay for. The fact that reverse supply chain may not (always) make revenue, the objective is to minimize the reverse logistics cost. Cost items are composed of the fixed cost of recycling operation in the recycling facilities, employment cost, fixed and variable cost of transportation, penalty cost of uncollected items. On the other hand, income is earned out of sales of the material obtained from recycled WEEE. TR defines the target cost, and since the goal is to catch a break-even point, this is set to zero. Constraint (6) denotes legal collection goal taking into account actual sales (Sm_{it}) and the amount of product (X_{ikt}) decided to collect in that period. There is a legal requirement that at least O_{it} percent of the sold goods are recycled. Constraint (7) describes environmental effect of each products' recycling operation in the facility and each truck sent to collect the products. The total emission goal (ε_t) is set with regard to total emission expected from all operations.

Minimization of the negative deviation (p_{lt}^-) from the employment target is aimed at the third objective. Related with this objective, Constraint (8) stipulates that the number of workers in

each facility (W_{lt}) should be close to the employment target. The structural Constraints (9), (10) ensures workforce is greater than required person-hour work and does not exceed the allowed maximum workforce level. Constraint (11) implies that sum of the workers employed in the previous period and those hired in the current period minus the redundant workers is equal to the current number of workers employed. Here, W_{lt} denotes the number of workers employed and H_{lt} denotes the number hired, in period-t. Constraint (12) defines the capacity for each facility. Thus, recycled products in each period cannot exceed the capacity of the facilities. Economic order quantity is provided by Constraints (13), (14). These two constraints are modeled as conditional constraints and ensure that a truck is sent to a collection point if at least the amount of products is equal to the economic order quantity. Here, Y_{kt} is a binary variable and makes constraint (14) equal to X_{ikt} which is greater than EOQ. Then, the constraint (13) becomes 0 due to $(1-Y_{kt})$. Otherwise, 0 is assigned to X_{ikt}. EOQ is determined as a full-truck load that must be satisfied to collect WEEE from a city. Constraint (15) provides that at least some certain percent of the demand is collected in each city and each period. This constraint prevents the model to collect no products so as to produce zero emission. On the other hand, constraint (16) ensures that the total collected amount of product in a period cannot exceed the total demand from first period to a relevant period. Constraint (17) imposes non-negativity restrictions while set of integrality restrictions for decision variables X_{ikt}, H_{lt}, M_{lt}, W_{lt}, Y_{kt} are imposed by constraint (18).

5. Solution methodology

In the literature, many different and improved versions of the Augmented ε-constraint method exist (Ehrgott and Ryan, 2002; Laumanns et al., 2006; Hamacher et al., 2007; Mavrotas, 2009; Mavrotas and Florios, 2013). Since the Augmented ε-constraint method 2 (AUGMECON2) (Mavrotas and Florios, 2013) was proved to have better performance than the others, we preferred to use this method as our solution algorithm. We applied AUGMECON2 as shown below (Mavrotas and Florios, 2013):

$$\min f_1(x) + eps \times \left(\frac{s_2}{fmax_2 - fmin_2} + 10^{-1} \times \frac{s_3}{fmax_3 - fmin_3} + 10^{-2} \times \frac{s_4}{fmax_4 - fmin_4}\right) \quad (19)$$

$$\text{Subject to}: \quad (20)$$

$$f_2(x) + s_2 = fmin_2 + t \times (fmax_2 - fmin_2)/q_2 \quad (21)$$

$$f_3(x) + s_3 = fmin_3 + t \times (fmax_3 - fmin_3)/q_3 \quad (22)$$

$$f_4(x) + s_4 = fmin_4 + t \times (fmax_4 - fmin_4)/q_4 \quad (23)$$

$$x \in S \text{ and } s_i \in R^+. \quad (24)$$

In this formulation, f_1 corresponds to 'Legal Function', f_2 corresponds to 'Cost Function', f_3 corresponds to 'Social Function' and f_4 corresponds to 'Environmental Function'. Surplus variables of the respective constraints are represented by s_2, s_3, and s_4, respectively. The maximum and minimum value of objective functions from the payoff table are $fmax_i$ and $fmin_i$ respectively. The range of f_i is $fmax_i - fmin_i$, t is the counter of the interval (if f_i is divided to 4 then t changes from 1 to 4) and q_i is the length of the equal intervals of the objective function f_i, and ε is relatively a small number between 10^{-6} and 10^{-3} (Mavrotas and Florios, 2013). The identification of Pareto-optimal solutions is essential in multi-objective optimization. Thus we used CPLEX solver of the GAMS® software to generate a set of Pareto optimal solutions.

6. Case study

We illustrate our proposed model on a case study with real data and analyze the results. Some operational decisions are made for a global white appliances manufacturer. From manufacturers viewpoint, recycling of WEEE is very important in terms of fulfilling the responsibilities. In addition, WEEE collection rates are rising at a rapid pace due to the legal regulations (Ministry of Environment and Urbanization, 2012).

In the current setting, the customers have the right to return their used electrical-electronic products when they purchase a new one. So, as soon as the technical service provider of the manufacturer delivers the new product to the customer, he/she should take back the old one (WEEE), if the customer demands. Besides, electrical-electronic product manufacturers are obliged to take back some certain percent of their sales amount (legal target). Otherwise, high monetary penalties incur to the manufacturer. So, these conditions are valid in this case study. In Table 3, we present the required information about the case.

The network comprises customers, local collection sites of WEEE, and recycling centers, as well as transportation links among them. The reverse logistics system works in such a way that when customers buy a new product, they have the right to deliver waste appliances. Therefore, technical service of the manufacturer receives and stores the WEEE in its own warehouse. A third-party logistics provider is responsible for collecting the WEEE from all service points and delivering to recycling facility. In the recycling facility, products are initially stored in the collection center, which is in the same location with the facility. When they are ready to be processed, they are sorted and recycling operations start. Different types of output materials are obtained such as iron, aluminum, copper, compressor, plastic, wire, recyclable CFC (chlorofluorocarbon), glass. These materials are sent to different facilities according to their specifications. Fig. 2 describes the focal point of the optimization model in reverse supply chain network. It starts with the collection of WEEE and ends with the recycling processes at the facilities. Therefore, a collection decision is made for each period by considering the pre-determined goals in the proposed model.

In this case, there are two recovery facilities. The location of the recovery facilities is pre-determined. So, no facility location decision is made. WEEE products accumulate in the local collection points of the 81 cities. 12 months-period is considered. The distances between the city centers and the facilities are used in the model. There are three types of products' WEEE to be recovered, namely refrigerator, washing machine and dish-washer. Refrigerator is recovered at the first facility, where the other two types of WEEE are recovered in the second one.

Monthly target recovery ratios for all products are assumed as 5%, which means at least 5% of the sold products should be recovered ($O_{it} = 5\%$). The total sales quantities of these three products are known. The target employment levels are 8 and 12 for the first and second facilities, respectively ($Employment\_target_{1t} = 8$, $Employment\_target_{2t} = 12$). The target cost is assumed as zero ($TR_{it} = 0$), so that the operational and transportations costs are offset by the sales revenue earned out of the materials recovered. The total CO2 emission target for the recovery & transportation operations is 55,000 kg/month ($\varepsilon_t + \beta_t = 55,000$ $kg/month$). This emission target is determined in accordance with

Table 3
Settings of the case study.

# of city	81	all cities over the country
# of facility	2	1: refrigerator, 2: washing machine and dish-washer
# of product type	3	1: refrigerator, 2: washing machine, 3: dish-washer
collection target (%)	5	legal target for 2016
cost target ($)	0	set as breakeven point
environmental target (kg/month)	55000	emission stem from in-facility and transportation operations
employment target	8 (1. facility), 12 (2. facility)	
transportation vehicle engine	Euro5 or higher	
recycled materials	iron, aluminum, copper, compressor, plastic, wire, recyclable CFC (chlorofluorocarbon), glass	

the WEEE recovery demand during a year, the expected number of vehicles, and the energy consumption of the recovery operations in the facilities. The model forces not to exceed this CO_2 emission target.

In this case, the stock out cost is not needed to be considered since there is no demand to be satisfied by the customers in the supply chain to recover the waste material in a certain period. Besides, inventory holding cost does not actually incur to the recovery facility/company, since there is no investment in the WEEE that is collected. There is no purchasing cost of WEEE to the recovery company. Besides, there is enough available space to keep the waste inventory.

7. Results and discussion

The model was solved lexicographically using the GAMS® software, CPLEX solver, by a notebook computer with a 1.7 GHz Intel core i5 CPU and 4 GB RAM running Windows 10. Table 4 presents the statistics and the solution report of the model. The goal programming model includes 42044 equations, and 7030 variables where 6876 of them are discrete variables. When we solved the model for the legal objective, it took only 0.188 s to reach the optimum. Then the goal programming model is converted into an ε-constraint model. It has four additional equations, and additional (slack) variables. When this model is also solved, it took around 0.328 s. The computational times are very short.

Based on the solution of the ε-constraint model, the payoff table is obtained as shown in Table 5. We can see from the pay-off table (Table 5) that if we optimize the legal target, we can obtain minimum 8948 uncollected items. In the meantime, total cost becomes 687,163.844$, the total deviation from employment target becomes 7 persons in total and, the total deviation from environmental target becomes 203,234.95 kg. When we optimize the economic target, we can obtain minimum 667,692.730$ total cost with 21,956 uncollected items, the total deviation of the employment target of 22 persons and the total deviation of 72,152 kg emission. In this case the target emission level is exceeded approximately by %15. Therefore, Euro5 vehicles cannot reach the emission target, when the problem is solved according to legal, economic and social objectives. Also, social target is obtained 5 that is minimum which indicates the deviation from employment target during all periods. Lastly, we obtained zero deviation from the desired emission level when we solved according to the environmental target. By using the parameter values presented in the payoff table, the range values of each objective function were determined, based on the AUGMECON 2 (Mavrotas and Florios, 2013). Based on the intervals of $fmax_i - fmin_i$ values for f_2, f_3, and f_4, the solution of the problem generated 60 unique Pareto Optimal solutions, and those are shown in Appendix A, Table A.

Because our model has four different goals, the results are influenced by each goal. Therefore, we solved a bi-objective version of the model by fixing the rest of the two other goals to observe the

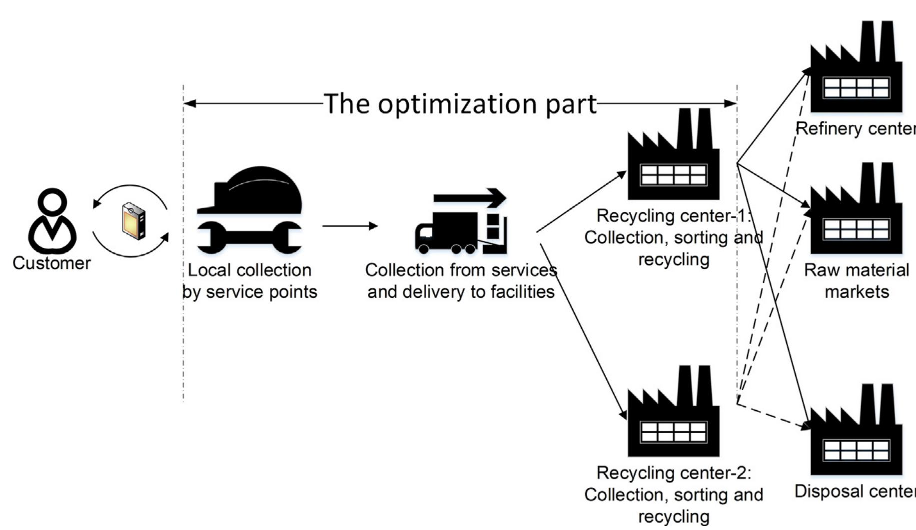

Fig. 2. Reverse logistics network.

Table 4
Model solution statistics for case study.

	Number of						
	Blocks of equations	Blocks of variables	Single equations	Single variables	Nonzero elements	Discrete variables	Execution time (s)
Goal programming	36	18	42044	7030	268829	6876	0.188
ε-constraint model	40	22	42048	7034	268911	6876	0.328

Table 5
Pay-off table obtained.

	Z1 (legal)	Z2 (economic)	Z3 (social)	Z4 (environmental)
Min Z1 (legal)	**8948**	687163.844	7	203234.95
Min Z2 (economic)	21956	**667692.730**	22	72152.00
Min Z3 (social)	56075	978431.485	**5**	206964.3
Min Z4 (env.)	56066	959096.742	39	**0**

relationship between economic goal with the other goals. Fig. 3(a) shows the economic goal (net cost) versus legal goal (number of uncollected items). The number of uncollected items gradually increases as the cost decreases, in a non-linear way. Fig. 3(b) shows the economic goal versus environmental goal. The cost remains approximately constant over a range of emission values. If the emission value gets closer to the target emission value, the cost increases. If the emission value is far from the emission target, the cost is also increasing. The reason behind this increase is the longer routes that the trucks use to collect the products. Fig. 3(c) shows the economic goal versus social goal. Starting from least possible social goal, the total cost sharply decreases and then gradually continues to decrease, as the social target reached becomes worse. A small improvement in the social goal requires a higher increase in the cost, when the (social) target is reached.

The results from the Pareto-optimal solutions table in the appendix A show that when we want to reach WEEE collection target with the social and environmental goals, the total cost is increasing considerably. For example, at the 36th Pareto optimal solution total cost is 745,377 $ while total number of uncollected

Fig. 3. The effect of economic goal (net cost) versus (a) number of uncollected items (legal target) (environmental target: 102500, social target: 18), (b) environmental goal (legal target: 17500, social target: 18) (c) social goal (legal target: 17500, environmental target: 102500).

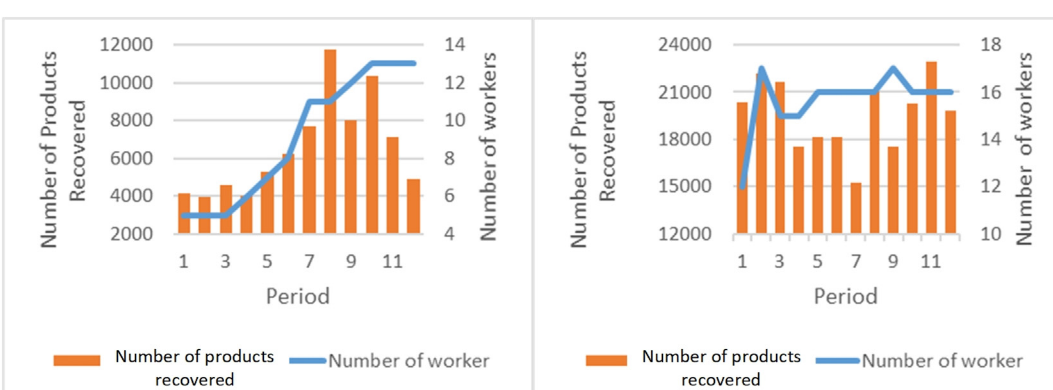

Fig. 4. Comparison of workers in the both facilities with the number of products recovered (WEEE demand) in each period. (a) Number of workers at refrigerator recycling facility (b) number of workers at white goods recycling facility.

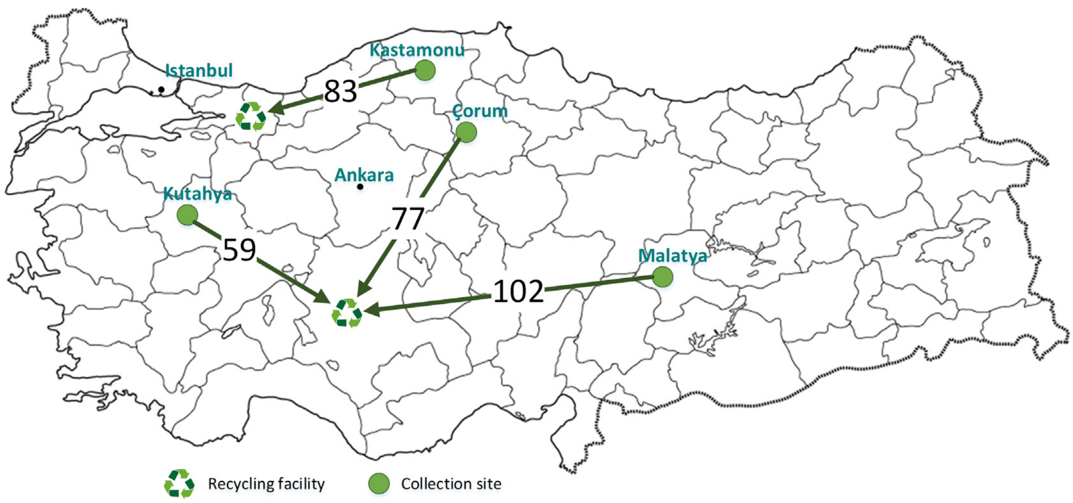

Fig. 5. Amounts of WEEE Collected at the 15th Pareto optimal solution for the 3rd period.

items is 11,072 items, total emission value is 152,355 kg CO_2 and negative deviation from employment target is 39 persons. On the other hand, total cost is 823,062 $ at the 48th Pareto optimal solution while total number of uncollected items is 10,551, total emission value is 155,223 kg CO_2 and negative deviation from employment target is 22 persons. It is also worth noting that the total cost does not vary linearly, as one target decreases and the other increases. For this reason, the obtained Pareto optimal results must be evaluated by experts.

Fig. 4 represents the number of workers at two of the facilities and the number of products recycled in each period (WEEE demand) according to the 15th Pareto optimal solution. The first facility only recycles refrigerators and the demand peaks during months 8, 9 and, 10 (see Fig. 4(a)). The exact number of refrigerator recycled in Fig. 4(a) is around 4800 items during the first six months although it reaches 12,500 items at the eighth month. On the other hand, the second facility recycles rest of appliances. It recycles around 240,000 items in a year. For this facility the demand decreases at the mid of a year. Although the demand (number of products recycled) varies considerably, it appears that the variability in the number of workers in both facilities are less. The reason for this situation is to reach the social goal.

Fig. 5 describes an example of the obtained the results for collection decision at the 3rd period. Results indicate that 59 refrigerators from Kutahya city, 77 refrigerators from Corum city and 102 refrigerators should be collected from Malatya city to refrigerator recovery facility and from Kastamonu city 83 products should be collected to the white appliances recovery facility on March (3rd period).

8. Conclusions

This paper optimizes operations planning of reverse supply chain network with the Triple Bottom Line accounting perspective. In this study, for a case study of durable goods recovery company, the goals were defined by the legal regulations and sustainability dimensions. According to the laws, the manufacturers are required to recover a minimum percent of their goods sold, and loyalty to the regulations is important. Therefore, the legal target is set to catch the collection target. Besides, an economically sustainable business is vital for the companies. For this reason, the goal of not to incur loss (zero cost target) is determined as an economic objective. Because of the fact that it is not highly possible to make profits in recycling systems, loss minimization was defined instead of profit maximization. When the companies are considered to be responsive to the employees, it is very important that they can provide permanent employment to their employees. In spite of variability in the demand of WEEE, the social goal is set to catch employment target which is defined according to the capacity of facilities and demand. In order to provide also environmental responsibility, an emission target is determined while optimizing the network. So the goal is not to exceed the determined CO_2 emission level. Therefore, manufacturers are driven to change transport vehicles with more efficient and greener engines (Euro6 engines). The solution of the resulting mixed-integer linear goal programming model was provided by an implementation of the AUGMECON-2 in GAMS® software.

For all that, this model is used for a case of a global white appliances manufacturer; it can be generalized for producers like all types of electric and electronic equipment (EEE) producers, automotive supply industry or health sector. Nevertheless, some sectors do not have legislations on waste products. In this case, the optimization model can also be run without a legal goal. In addition, some additional environmental constraints can be added according to the product structure. In future studies, due to the uncertainties in number of products to be recycled (demand), and prices of the recovered materials, stochastic optimization techniques can be employed. Besides, reverse logistics of other types of products other than WEEE can be planned, and different social objectives can be set, in future studies.

Disclosure statement

A potential conflict of interest was not reported by the authors.

Acknowledgement

This study has been financially supported by the Istanbul Technical University, with the project numbered 39770.

Appendix A

Table A
Pareto Optimal Solutions for the case study.

Experiment #	Z1	Z2	Z3	Z4	Experiment #	Z1	Z2	Z3	Z4
1	15.377	745.377	39	51.741	31	12.454	978.431	39	103.482
2	15.033	978.431	31	51.741	32	12.443	900.747	14	103.482
3	14.858	900.747	22	51.741	33	11.414	823.062	31	154.524
4	14.858	978.431	22	51.741	34	11.307	900.747	14	155.223
5	14.805	823.062	22	51.741	35	11.219	823.062	14	155.223
6	14.763	823.062	14	51.741	36	11.072	745.377	39	152.355
7	14.722	745.377	14	51.741	37	10.974	823.062	39	155.223
8	14.559	900.747	31	51.741	38	10.866	978.431	22	155.223
9	14.532	823.062	31	51.734	39	10.812	745.377	14	155.223
10	14.521	900.747	14	51.740	40	10.728	900.747	39	155.223
11	14.516	978.431	39	51.718	41	10.649	745.377	22	154.273
12	14.514	823.062	39	51.741	42	10.645	900.747	31	155.223
13	14.496	745.377	22	51.733	43	10.645	978.431	31	155.223
14	14.490	978.431	14	51.741	44	10.625	745.377	31	155.209
15	14.488	900.747	39	51.741	45	10.608	900.747	22	154.064
16	14.485	745.377	31	51.741	46	10.561	978.431	39	155.223
17	13.518	823.062	22	103.482	47	10.560	978.431	14	155.137
18	13.349	900.747	31	98.190	48	10.551	823.062	22	155.223
19	13.349	978.431	31	98.190	49	9.209	900.747	22	206.471
20	12.959	900.747	22	103.482	50	9.097	745.377	14	206.964
21	12.942	823.062	39	103.482	51	9.096	978.431	22	205.640
22	12.839	978.431	22	103.482	52	9.089	900.747	14	206.964
23	12.766	745.377	39	103.482	53	9.089	978.431	14	206.963
24	12.731	745.377	14	103.482	54	9.045	823.062	14	206.964
25	12.566	978.431	14	103.482	55	9.043	823.062	39	206.964
26	12.507	823.062	14	103.482	56	9.043	900.747	31	205.906
27	12.493	745.377	31	103.482	57	9.004	900.747	39	206.964
28	12.484	823.062	31	103.482	58	8.977	823.062	22	206.964
29	12.474	745.377	22	103.482	59	8.967	745.377	39	206.964
30	12.454	900.747	39	103.482	60	8.951	978.431	31	206.964

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